EXECUTIVE REPORT

FULL-SCALE SHAKE TABLE TESTING OF A TWO-STORY MASS TIMBER BUILDING WITH RESILIENT ROCKING WALL LATERAL SYSTEM

Prepared for Softwood Lumber Board by:

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Table of Contents

Introduction

This report is prepared for Softwood Lumber Board (SLB) by the NHERI TallWood Project team in order to provide a brief and timely update on the progress and preliminary research findings from the NHERI TallWood Project. This report is focused on the full-scale shake table test of a two-story mass timber building conducted during the summer of 2017 at NHERI@UC San Diego outdoor shake table.

The shake table test described in this report was conducted during a three-month period from June to August 2017. As the research team is still working on processing and analyzing the data obtained from the experiments, this report only discusses preliminary findings in a qualitative manner. The research team is expected to produce additional reports and publications based on the test results in the near future. Inquiries on additional information about the testing program may be directed to NHERI TallWood Project PI, Dr. Shiling Pei at Colorado School of Mines (spei@mines.edu).

As one of the industry partners of the NHERI TallWood Project, SLB provided significant financial support to the 2017 testing program. The NHERI TallWood Project team would like to acknowledge this valuable support and look forward to further collaboration with SLB on this project and other mass timber research topics that will help advance and expand the wood building market.

This report was organized into five sections that address key questions about the testing program and findings. The background and motivation of the experimental research was discussed first, followed by the scope of the test program. The preliminary findings and the potential impact of the new knowledge to the wood building market were discussed next. Lastly, a guide for interested readers who need additional information was provided.

Motivation: Why conduct such a test?

Rising interests in mass timber construction

Wood buildings in the U.S. has been predominantly constructed using platform light-framed wood construction for decades. Light-framed wood system is very cost-competitive in the low-rise residential market, but its application is restricted by the current building code in terms of height and area, making is less competitive in commercial applications and tall buildings. In addition, because of the use of wood bearing walls as the main gravity system, it is difficult (or costly) for light-framed wood buildings to have an open floor plan for commercial applications.

Since the introduction of Cross Laminated Timber (CLT, see Figure 1) into the U.S. in the early 2000's, there is an on-going effort to expand the wood building market beyond low-rise construction using mass timber construction, namely a combination of CLT and heavy timber elements to building taller and larger buildings that can be categorized better than Type V in IBC. Some of the recent projects even pushed further to exceed TYPE IV (HT) limits by following alternative performance-based approval paths, such as the recently completed Carbon 12 building in Portland OR and Brock Commons at UBC. By 2017, there are mainly two approaches to build mass timber buildings:

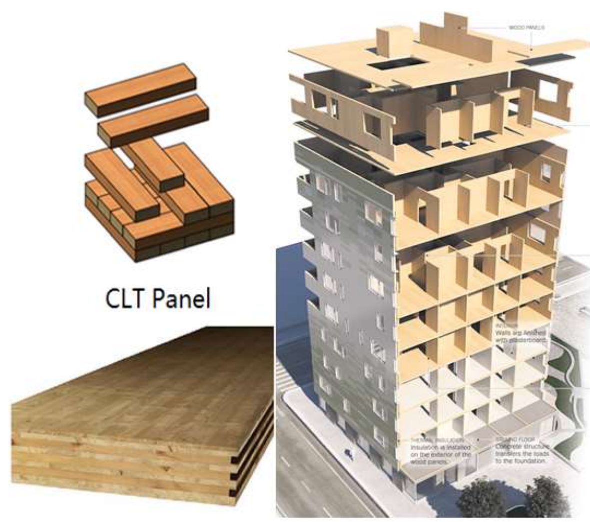

Fig.1: Cross Laminated Timber panel and example CLT building (Murray Grove, UK)

1) Platform CLT bearing wall construction similar to the Forte building in Melbourne, Australia.
2) Combining wood gravity system (CLT/NLT diaphragm + heavy timber framing) with traditional steel or concrete lateral system, such as the T3 building in Minneapolis.

Option (1) shares the same architectural limitation as light-framed construction that open (or reconfigurable) floor plan is hard to achieve. Option (2) originated from the lack of seismic design provisions for mass timber lateral system in current building code (thus the designers will use existing non-wood systems). There is currently no codified all-wood design option for an open-floor plan mass timber building for regions affected by earthquake hazard.

How to make a new system competitive?

It is relatively easy to see the need for an open-floor plan in mass timber construction. Because this feature helps push mass timber construction into commercial building market where light-framed wood construction is not very competitive. But is there really a need to replace concrete or steel frame lateral system with a wood system from a market standpoint? Could we just use concrete shear walls and steel braced frames for the elevator cores and use wood floor/framing? It may seem like too much effort for too little gain to replace the lateral system in a commercial building with wood. Because it is only a small fraction of all wood used in a building. But the answer to this inquiry lies beyond just the added volume of wood. It is a matter of offering the wood option a competitive edge by providing significantly better seismic performance than existing steel and concrete systems.

In order to break into an existing market, a new product has to either offer the same performance at a lower price, or offer much better performance at the same price. As of today, it is very difficult to offer a mass timber design at the same price as non-wood options. So a significant boost of performance in mass timber design is worth pursuing. In term of seismic performance, there is fortunately plenty of room for improvement in current building code standards.

Most of existing commercial buildings were designed to meet building codes, which is a set of minimal requirements that ensures life-safety. This means after a strong earthquake, these buildings are expected to remain standing without collapse, but will experience costly damage or even need to be demolished. If mass timber buildings continue to use existing code-complaint concrete or steel lateral systems, the damage to these buildings will be similar to that of concrete and steel buildings, which is very costly. **So what if mass timber buildings can become earthquake-proof by using new wood-based lateral system?** This is the key motivation of this research project.

NHERI TallWood Project

In 2016, NHERI TallWood Project was funded by the National Science Foundation to develop and validate resilience-based seismic design methodology for tall wood buildings. In a 4-year period (2016~2020), the project team plans to develop a new mass timber building type that can withstand large earthquakes without significant loss of use for building owners/occupants. This design approach will be validated in 2020 by testing a full-scale 10-story mass timber building at the world's largest outdoor shake table in San Diego. The NHERI TallWood research team and the planned research activity over the project period are shown in Figure 3 and 4.

The two-story building shake table test conducted in 2017 is one of the investigative tests planned to validate the performance of the proposed mass timber building system with CLT rocking walls. To date, full-scale shake table test of a mass timber building with resilient rocking wall system has not been done world-wide. All existing shake table tests (including test at E-Defense shake table by Italian and Japanese researchers) on CLT construction were on platform CLT wall systems, which was shown to experience damage during strong shakes. The research team is expecting resilient (damage-free) performance for the two-story building during large earthquakes. The data collected in the two-story test will be used to guide the design of the 10-story building that will be tested in 2020.

Fig.3: NHERI TallWood Project team and participants

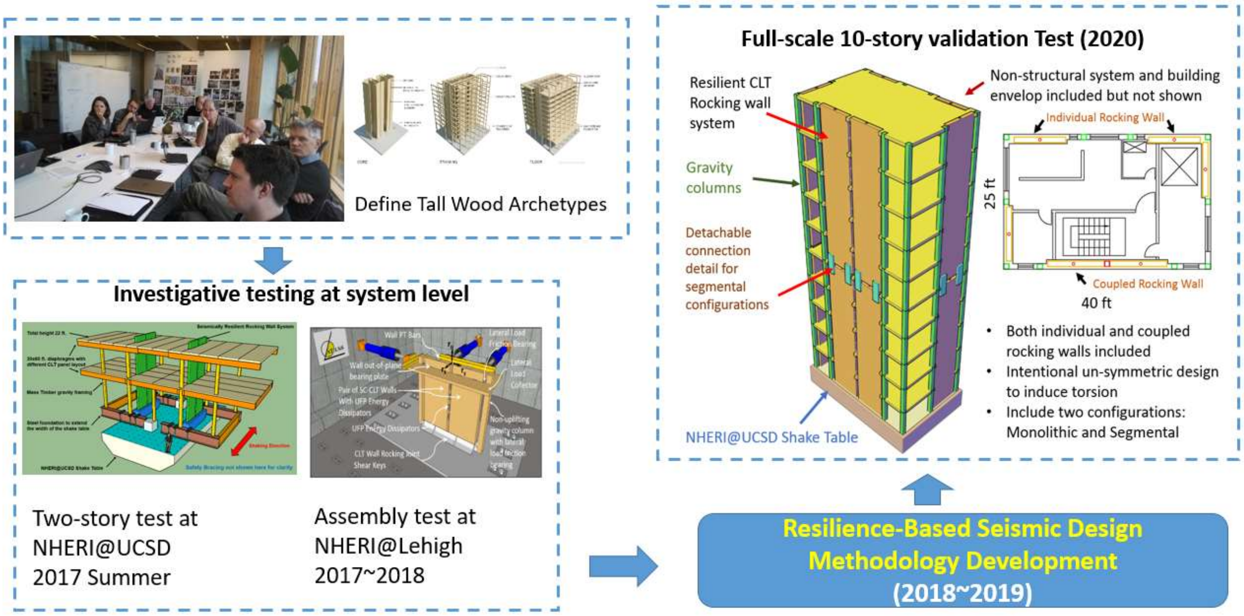

Fig.4: Tentative timeline and research plan for NHERI TallWood Project

In summary, the motivation of this research is to develop the technology that can enable mass timber commercial buildings that can perform significantly better than current steel and concrete buildings in large earthquakes. It is believed that the results of this project will encourage adoption of all-wood building systems in earthquake affected regions because of their resilient performances.

Scope: What was tested?

Specimen design

The test building and test program were designed to answer following key questions:

1) Can we achieve damage-free performance in an open-floor plan wood building through use of post-tensioned CLT rocking walls?
2) How to design the gravity frame system so it can tolerate large lateral drift without damage?
3) How to design lateral force transfer between the building diaphragms and rocking walls?
4) How to design CLT diaphragms to have adequate performance in large earthquakes?

These considerations led to a 22-ft tall test building (12 ft at first floor, 10 ft at the second floor) with a 58 x 20 ft floor plan as shown in Figure 5. The specimen has a very open floor plan and relatively high diaphragm aspect ratio in the direction of the shaking. Two different diaphragm designs were implemented, including a wood-only diaphragm at the floor level and a concrete-CLT composite diaphragm

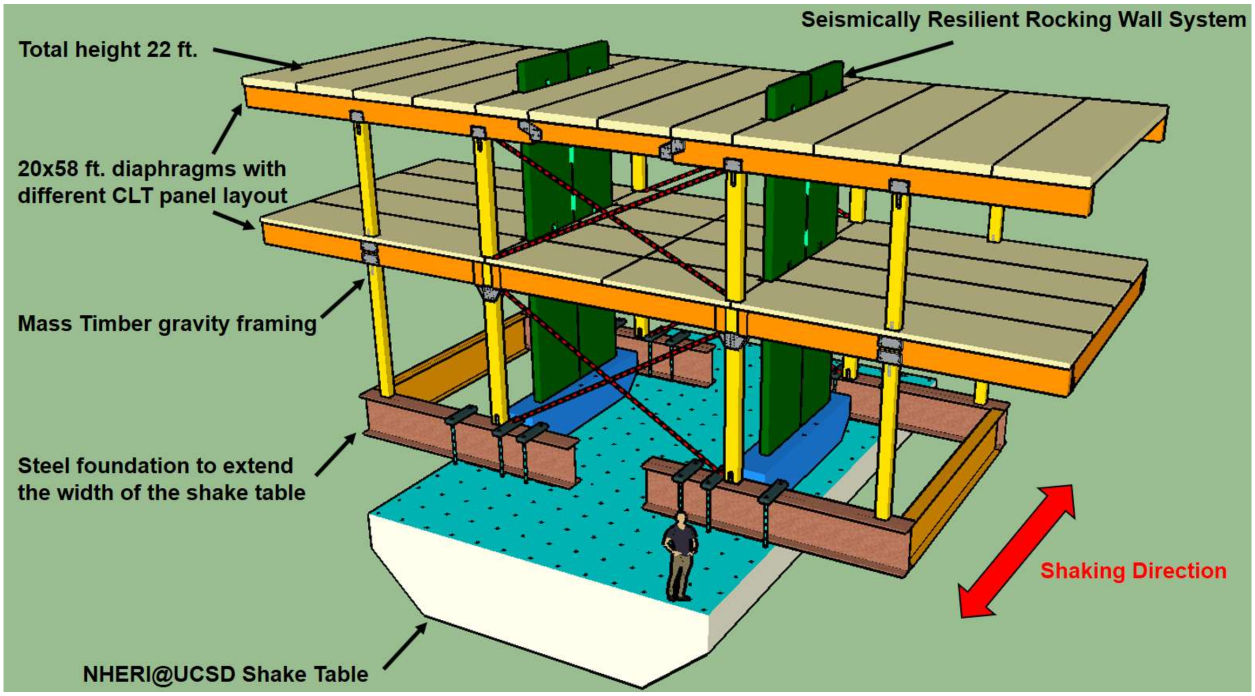

Fig.5: Two-story mass timber test building

design at the roof level (concrete topping not shown here). The diaphragm design was conducted by research collaborators (PI: Andre Barbosa) at Oregon State University through the support of Tallwood Design Institute.

The rocking wall system was designed for seismic hazard near San Francisco, CA by the NHERI TallWood research team in collaboration with KPFF. The shear transfer detail between the rocking wall and diaphragms was adopted from an existing KPFF project (the Mass Timber Parking Garage project at City of Springfield OR). The research team and KPFF engineers developed all details for the gravity frame using readily available connection products from Simpson Strong-Tie catalog (with some minor adjustments). Several custom steel connection parts were also made as needed.

All of the CLT panels and glulam members were purchased at a discounted price from DR Johnson Lumber. All the diaphragm panels are V1 grade per APA PRG-320. The rocking wall panels are grade E2-M1. High strength Simpson ATS all-threaded rods (5/8" diameter with yielding strength about 30 kips) were used as the post-tension rods.

Construction process

The construction of the test building was contracted to Seagate Structures Ltd. American. There were two carpenters on site during the construction process. The UCSD site crew (two persons) helped to operate the crane. The construction of the wood gravity frame only took four days. The preparing and pouring of the concrete composite layer was done by a different contractor after the wood frame was completed. After the concrete hardens, the CLT rocking walls were inserted into the building and connected to the diaphragm and the foundation. During this process, additional steel trench plates were also placed on the floor and the roof in order to bring the total seismic mass to the design level. The last step of construction is the post-tensioning of the rocking wall. Because the needed post-tension force level is relatively low, the post-tensioning was achieved by tightening the nuts manually while monitoring the tension forces using load cells. Key steps in the construction process were illustrated in Figure 6. The completed building was shown in Figure 7.

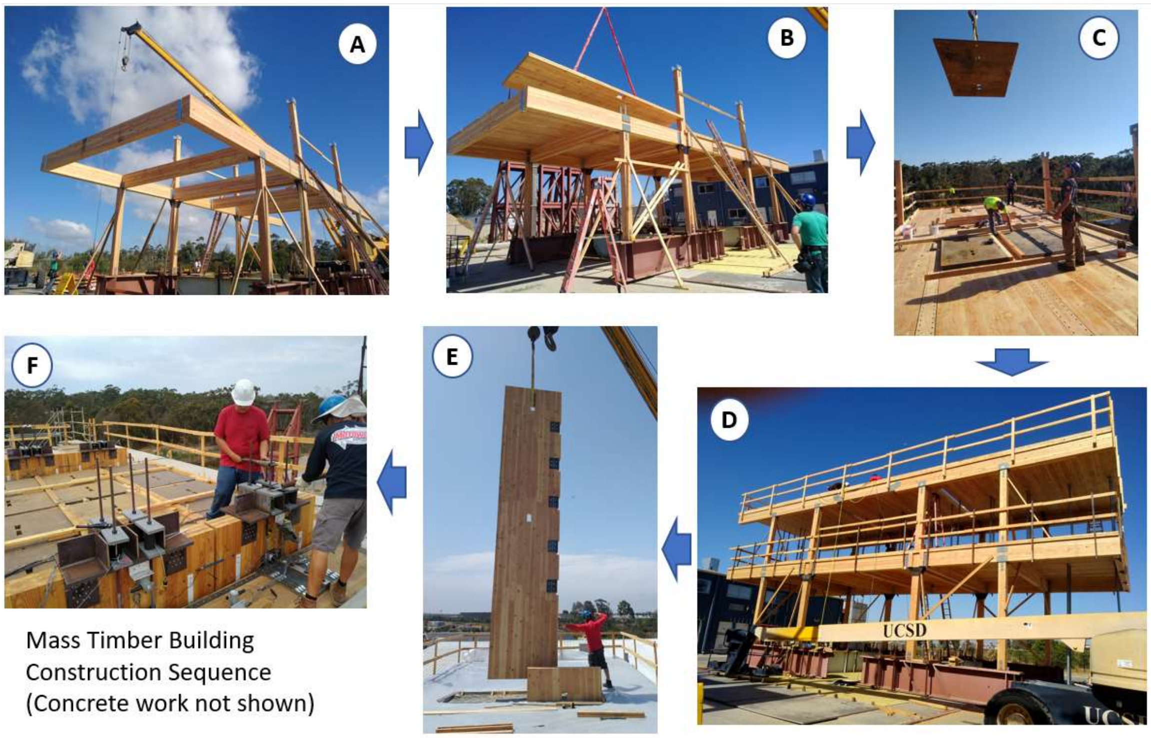

Fig.6: Construction process (wood only)

Fig.7: Completed test building

Testing program

Earthquake ground motions recorded from historical earthquakes were used in the testing program, including ground motions from the Northridge and Loma Prieta earthquakes. These ground motions were scaled to represent different hazard levels based on the seismic design map. There are three hazard levels tested, namely the service level earthquake (SLE), design basis earthquake (DBE), and maximum considered earthquake (MCE).

The research team hosted two public testing events, in which the original Northridge ground motion record was applied to test building twice in a row. These tests were planned in order to demonstrate the ability of the building to withstand two large earthquakes consecutively without the need to repair. On the last day of testing, after imposing multiple MCE ground motions without damaging the building, the researchers increased the scale factor of the ground motion to 120% of the MCE level in order to yield some of the post-tension rods.

All shake table tests conducted on the post-tensioned rocking wall system are listed in Table 1. Because it is not possible for the shake table to completely reproduce the ground motion inputs (this is common for large shake tables), the peak ground acceleration (PGA) and spectral acceleration (Sa) values listed in the Table were obtained from the measured actual acceleration from the shake table. The spectral acceleration values were given at 0.9 second natural period because that is close to the measured natural period of the building. The response spectrum of the ground motions at different levels were plotted in Figure 8.

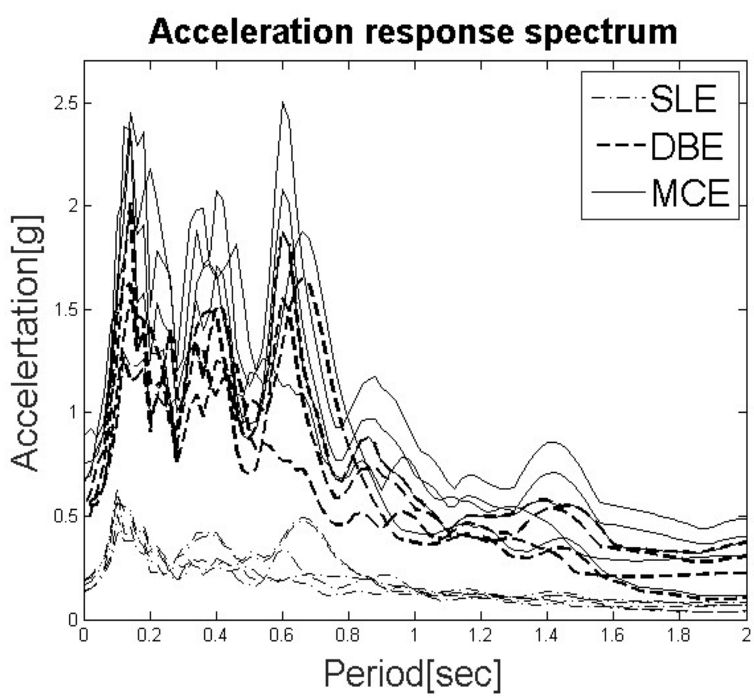

Fig.8: Response spectrum of the ground motions

Table 1. Ground motion used in the test

ID	Ground Motion	Hazard level	PGA (g)	Sa @ 0.9 sec (g)
1	Loma Prieta	SLE	0.17	0.16
2	Loma Prieta	SLE	0.19	0.16
3	Northridge	SLE	0.19	0.18
4	Superstition Hill	SLE	0.13	0.12
5	Northridge	DBE	0.54	0.70
6	Northridge Repeated	Original	0.56	0.76
7	Imperial Valley	SLE	0.14	0.22
8	Northridge Repeated	Original	0.55	0.76
9	Loma Prieta	DBE	0.54	0.50
10	Superstition Hill	DBE	0.48	0.43
11	Loma Prieta	MCE	0.66	0.58
12	Northridge	MCE	0.76	0.92
13	Superstition Hill	MCE	0.68	0.63
14	Northridge	MCE x 1.2	0.89	1.12

Additional tests on other structural systems were also conducted after the test of the post-tensioned rocking wall system. A rocking wall system with replaceable components (see Figure 9) was designed and constructed by Katerra and tested under 13 ground motion excitations. Following that test, platform CLT panel shear walls (Figure 9) were tested following the newly developed seismic design parameters and procedure from the CLT shear wall P695 project (PI: John van de Lindt, Colorado State University). The platform CLT wall tests were funded by the Forest Products Lab.

CLT Rocking Wall by Katerra   Platform CLT shear wall

Fig.9: Additional CLT lateral systems tested

Although the lateral system of the test building was changed during the testing period, the gravity frame and diaphragm system remained the same and withstood a total of 34 earthquake excitations. There is no major damage on the gravity system and diaphragm throughout all earthquakes, highlighting the resilient performance of the gravity frame and diaphragm design.

Findings: What did we learn from test results?

The building was tested to achieve a maximum of 5% inter-story drift during the final test beyond MCE hazard level. This is the drift level at which one will expect severe damage and yielding in concrete or steel systems. But the mass timber building experienced no major damage. Some post-tension loss was observed in MCE level tests, but was easily repaired by re-tightening the post-tension rods. The post-tensioned rocking wall was able to keep the building re-centered even with the post-tension loss. The building residual drift was under 0.5% for all tests conducted. The glulam beam-column connections performed very well during dynamic testing, and showed no visible damage after 14 ground motions. The diaphragm remained elastic and rigid with no signs of permanent slip or deformation.

The only visible damage was found at the bottom corners of the rocking wall panels. The damage was mostly cosmetic including splitting of the outside wood fiber and slight deformation of the corner. After the test was completed and the rocking walls were taken out of the building, slight compression deformation at the rocking wall toe was observed. But all the damage (see Figure 10) did not affect the performance of the system thus require no repair. The resilient performance target was verified by the test structure.

Slight compression deformation at the rocking wall corner

Chipping of wood at the rocking wall corner

Fig.10: Observed damage to the rocking wall toe

Following conclusions can be drawn from preliminary observation of the test results:

1) It is possible to combine a CLT rocking wall system with a heavy timber gravity system to achieve resilient performance under large earthquakes at DBE and MCE intensity levels. An open-floor plan mass timber building can be structurally damage-free under multiple earthquake excitations.
2) This resilient performance is significantly better than typical seismic performance observed in most of the existing non-wood systems. In addition, this design enables very fast construction by a small on-site crew.
3) By using simple connection detail and connectors readily available on the market, CLT diaphragms can be designed to adequately transfer lateral forces under large earthquakes.
4) The shear transfer detail between the diaphragm and rocking wall performed very well during large earthquakes. Over-strength for such details is recommended in their design in order to keep them elastic under earthquake loading.
5) The gravity connection details used in this test program can tolerate up to 5% inter-story drift without inducing damage or losing stability.

Impact: What does it mean for the wood industry?

Although this test is only the first experimental study of the NHERI TallWood Project, the successful demonstration of the resilient performance of a two-story open-floor plan mass timber building can already provide some support for expanding wood building market.

Even if we only work under the current IBC framework, mass timber buildings can be permitted as Type IV construction and were allowed to be constructed up to 85 ft. Within this height range, the structural design approach implemented in the two-story test structure can be directly adopted to achieve structural resilience in regions of high seismicity. For example, the office buildings shown in Figure 11 were typically constructed using steel or concrete systems. But now we have solid proof that there is significant resilience benefit to the owners if a wood building with post-tensioned rocking wall system is used. Combined with the accelerated construction time, savings on foundation cost due to reduced weight, and environmental benefits, a potential boost in the low-to-mid-rise mass timber commercial building market is possible. But this requires an effective technology transfer (e.g. a design guide document with examples) that can enable design engineers to replicate what was achieved in the testing program.

Fig.11: Example open-floor plan office buildings that could be suitable for wood construction (Left: Office at the Millennium Business Centre, Auckland NZ; Right: Dandenong Government Services Office, Melbourne AU)

Follow-up: Where to find additional information?

The NHERI TallWood research team is currently still in the process of verifying, organizing, and analyzing the data obtained from the tests. The design and construction of the test building was documented but the organization of such information into a publishable form will take additional time and efforts. The research team is expected to prepare and made available more detailed reports on the test program later in 2018. If there is any request on specific information before these reports are completed, please contact NHERI TallWood Project PI Dr. Shiling Pei at Colorado School of Mines (Email: spei@mines.edu Ph: 303-273-3932).

Several research papers will be prepared and submitted to peer-reviewed journals on the research findings, including ASCE Journal of Structural Engineering. Due to the journal review cycle, it is expected these papers will become available to share in the latter half of 2018.

There are a few major engineering conferences in 2018 in which the research team has planned to present testing results. These conferences include:

- March 20~22, Mass Timber Conference, Portland OR
- April 19~21, ASCE Structures Congress, Ft Worth TX
- June 18~21, 16th European Conference on Earthquake Engineering, Thessaloniki, Greece
- June 25~29, 11th National Conference on Earthquake Engineering, Los Angeles CA
- August 20~23, World Conference on Timber Engineering, Seoul, South Korea

More dissemination efforts may be added as time goes on. If there is a need to coordinate the dissemination at these events, please contact the project team.

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The opinions presented here are solely those of the authors and do not necessarily represent that of the sponsors.